New tools for cosmology by Extended Theories of Electro-Magnetism

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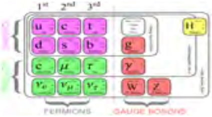
- GW detection 2015, but universe understanding is based on EM observations.
- Fundamental physics enquiries on the foundations (electromagnetism).
- 96% universe dark (unknown), only part of 4% is known: yet precision cosmology.
- Dark matter and energy: *ad hoc* suppositions and experimentally undetected. Observations: excess velocities, non-linear red shift with distance.
- Proposals of extended/alternative theories of gravity, but GR works.
- Complex interwoven, parametrised ΛCDM with <u>linear</u> EM theory of 19^{th} century.
- Special Relativity and Quantum Mechanics were born by reinterpreting light.
- The photon is the only free massless particle of the Standard Model.
- Shortcomings SM: $m_{\rm n} \neq 0$, matter-antimatter, Higgs too light ?, no darkness.
- There is no prejudice against a photon small mass: all radiative corrections are proportional to mass ('t Hooft).
- EM radiation $m_\gamma = 0$ ($v = c$). But it carries momentum-energy $\longrightarrow m_{\rm i} \neq 0$. For EP, $\longrightarrow m_{\rm g} \neq 0$. ('t Hooft).
- Einstein demonstration of $E = mc^2$ (wagon at rest on frictionless rails, photon shot end to end) implies m_γ.



Setting the scene

- $\Delta E \Delta t \geq \hbar/2 = \Delta m c^2 \Delta t \geq \hbar/2$ where $m = \hbar/c\bar{\lambda}$
- A photon of mass m_γ damps the interaction at a distance r by a factor $e^{-r/\bar{\lambda}}$, the reduced Compton length being $\bar{\lambda}[\mathrm{m}] = 3.52 \times 10^{-43}/m_\gamma[\mathrm{kg}]$. **Tinier photon masses may be thus sought through large scale measurements**.
- The lowest value for any mass is dictated by Heisenberg's principle $m \geq \dfrac{\hbar}{2\Delta t c^2}$, and gives **1.3**$\times 10^{-69}$ **kg**, where Δt is the supposed age of the Universe.
- No particle can be proven massless.
- Multimessenger astronomy should consider the PDG official upper limit of photon mass when considering the speedof light.

Impact of Generalised Maxwellian Theories (ETEM)

ETEM are massive, non-linear, associated to SME.

- ETEM predict, among other effects
  1. Dispersion: $v_g = v_g(f)$ - Fast Radio Bursts and Pulsars,
  2. Modifications of the Maxwell laws.
  3. Frequency shifts: $\Delta f/f$ additional to z the cosmological red-shift,

Massive theories: de Broglie-Proca

Louis de Broglie 1922-1923 defines $m_\gamma < 10^{-53}$ kg (PDG value 10^{-54} kg !). In 1936 dB writes the modified Maxwell's equations in a non-covariant form.

A. Proca, de Broglie's student, described electrons and positrons. Despite Proca's assertions on $m_\gamma = 0$, his Lagrangian has been used. For $F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha$.

$$\mathcal{L} = -\frac{1}{4\mu_0} F_{\alpha\beta} F^{\alpha\beta} - \frac{\mathcal{M}^2}{2\mu_0} A_\alpha A^\alpha - j^\alpha A_\alpha \tag{1}$$

ϵ_0 permettivity, μ_0 permeability, $\vec{j}$ current. $\mathcal{M} = m_\gamma c/\hbar = 2\pi/\lambda$, $\hbar$ reduced Planck (or Dirac) constant, c speed of light, λ Compton wavelength, m_γ photon mass.

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0} - \mathcal{M}^2 \phi , \tag{2}$$

$$\nabla \times \vec{B} = \mu_0 \vec{j} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} - \mathcal{M}^2 \vec{A} , \tag{3}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} , \tag{4}$$

$$\nabla \cdot \vec{B} = 0 , \tag{5}$$

The dBP equations are Lorentz-Poincaré transformation but not Lorenz gauge invariant, though in static regime they are not coupled through the potential.

Lorenz = Coulomb gauge if $(\partial\phi/\partial t = 0)$, $\nabla \cdot \vec{A} + \partial\phi/\partial t = 0$.

Massive theories: de Broglie-Proca

From the Lagrangian we get $\partial_\alpha F^{\alpha\beta} + \mathcal{M}^2 A^\beta = \mu j^\beta$, with the Lorentz subsidiary condition $\partial_\gamma A^\gamma = 0$,

$$\left[\partial_\mu \partial^\mu + \mathcal{M}^2\right] A^\nu = 0 \tag{6}$$

Through Fourier transform, at high frequencies (photon rest energy < the total energy; $\nu \gg 1$ Hz), the positive difference in velocity for two different frequencies ($\nu_2 > \nu_1$) is

$$\Delta v_g = v_{\rm g2} - v_{\rm g1} = \frac{c^3 \mathcal{M}^2}{8\pi^2}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) \ , \tag{7}$$

being v_g the group velocity. For a single source at distance d, the difference in the time of arrival of the two photons is (pulsar, FRB, low frequencies)

$$\Delta t = \frac{d}{v_{\rm g1}} - \frac{d}{v_{\rm g2}} \simeq \frac{\Delta v_g d}{c^2} = \frac{d c \mathcal{M}^2}{8\pi^2}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right)$$

$$\simeq \frac{d}{c}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) 10^{100} m_\gamma^2 \ . \tag{8}$$

Pulsar and FRB observations always show that lower frequency photons arrive later, but the effect is conservatively attributed to plasma.

- The Born-Infeld Lagrangian

$$\mathcal{L} = \sqrt{1+F} - 1 + j^{\mu} A_{\mu} \tag{9}$$

Avoidance of infinities out of self-energy $\phi(0) = 1.8541 \frac{e}{r_0}$.

- The Heisenberg-Euler Lagrangian

$$\mathcal{L} = -\frac{F_{\mu\nu}F^{\mu\nu}}{4} + \frac{e^2}{\hbar c}\int_0^{\infty} d\eta \frac{e^{-\eta}}{\eta^3} \cdot \left\{ i\frac{\eta^2}{2} F^{\mu\nu}F^{*}_{\mu\nu} \cdot \right.$$
$$\cdot \frac{\cos\left[\frac{\eta}{\mathfrak{E}_k}\sqrt{\frac{-F_{\mu\nu}F^{\mu\nu}}{2} + iF^{\mu\nu}F^{*}_{\mu\nu}}\right] + \cos\left[\frac{\eta}{\mathfrak{E}_k}\sqrt{\frac{-F_{\mu\nu}F^{\mu\nu}}{2} - iF^{\mu\nu}F^{*}_{\mu\nu}}\right]}{\cos\left[\frac{\eta}{\mathfrak{E}_k}\sqrt{\frac{-F_{\mu\nu}F^{\mu\nu}}{2} + iF^{\mu\nu}F^{*}_{\mu\nu}}\right] - \cos\left[\frac{\eta}{\mathfrak{E}_k}\sqrt{\frac{-F_{\mu\nu}F^{\mu\nu}}{2} - iF^{\mu\nu}F^{*}_{\mu\nu}}\right]}$$
$$\left. + |\mathfrak{E}_k|^2 + \frac{\eta^3}{6} \cdot F_{\mu\nu}F^{\mu\nu} \right\} \tag{10}$$

Vacuum polarisation occurs for $E_c > 1.3 \times 10^{18}$ V/m or $B_c > 4.4 \times 10^{9}$ T.

Photon-Photon interaction and Photon merge/splitting since NL theories relate to second order QED. Many experiments including at CERN.

LoSy breaking (LSV)

- Lorentz breaking: measurements depend on velocity and orientation. Poincaré breaking measurements depend on space-time point.
- $\mathcal{L}_{1,2}$ odd CPT (2 supersymetrised), $\mathcal{L}_{3,4}$ even CPT (4 supersymetrised)

The Lagrangian L_1 reads

$$L_1 = -\frac{1}{4\mu_0} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2\mu_0} \epsilon^{\mu\nu\sigma\rho} k_\mu^{\mathrm{AF}} A_\nu F_{\sigma\rho} \ . \qquad (11)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ are the covariant and contravariant forms, respectively, of the EM tensor; $\epsilon^{\mu\nu\sigma\rho}$ is the contravariant form of the Levi-Civita pseudo-tensor, and A_μ the potential covariant four-vector.
We observe the coupling between the EM field and the breaking vector k_α^{AF}.

The Lagrangian L_4 reads

$$L_4 = -\frac{1}{4\mu_0} F_{\mu\nu} F^{\mu\nu} + \frac{r}{2\mu_0} \chi_{\mu\nu} F_\kappa^\mu F^{\nu\kappa} + \frac{s}{2\mu_0} \chi_{\mu\nu} \partial_\alpha F^{\alpha\mu} \partial_\beta F^{\beta\nu} \ , \qquad (12)$$

The $\chi^{\alpha\beta}$ tensor is linearly related to the breaking tensor $k^{\alpha\beta\rho\sigma}$.
The s - mass^{-2} - parameter and the r - dimensionless - coefficient come from SuSy.

- Effective or real mass? Higgs (charged leptons, quarks, W, Z Bosons), CSB for (mostly) composite hadrons (baryons and mesons). Epistemologically evident?
- The effective mass upper value is compatible with experimental data.

In odd CPT**Class 1 (CFJ)** for $k_0^{\rm AF} = 0$ and $\vec{k}^{\rm AF}$, time and space components of the LSV vector, mass is proportional to the background vector.

$$m_\gamma = \frac{\hbar|\vec{k}^{\rm AF}|}{c}x \ , \tag{13}$$

where x is an angular factor (difference between the preferred frame and observer directions). In the photon rest frame, the angular dependence disappears. The time delays are similar to dBP

$$\Delta t_{CFJ} = \frac{dc|\vec{k}^{\rm AF}|^2}{2}\left(\frac{1}{\omega_1^2} - \frac{1}{\omega_2^2}\right)x \ . \qquad \Delta t_{dBP} = \frac{d\ m_\gamma^2 c^3}{2h^2}\left(\frac{1}{\omega_1^2} - \frac{1}{\omega_2^2}\right) \ . \tag{14}$$

In odd CPT **Class 4**, the integration of the photino leads to a mass arises related to the background tensor if SuSy.

$$m_\gamma = \left(\frac{1 - r\chi}{s\chi}\right)^{1/2} \ . \tag{15}$$

Deviations from the Ampère-Maxwell equation

de Broglie-Proca

$$\frac{\nabla \times \vec{B}}{\mu_0} = \vec{j} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} - \frac{m_\gamma^2 c^2}{\mu_0 \hbar^2}\vec{A}\ . \tag{16}$$

SME-LSV

$$\frac{\nabla \times \vec{B}}{\mu_0} = \vec{j} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} + \frac{k_0^{\rm AF}\vec{B}}{\mu_0} - \vec{k}^{\rm AF} \times \frac{\vec{E}}{\mu_0 c}\ , \tag{17}$$

where $k_0^{\rm AF}$ and $\vec{k}^{\rm AF}$ are SME parameters. For $k_0^{\rm AF} = 0$, $m_\gamma = \hbar|\vec{k}^{\rm AF}|x/c$.

NLEM Non-linear theories of electromagnetism $\mathcal{L} = \mathcal{L}(\mathcal{F}^n, \mathcal{G}^m)$ where

$$\mathcal{F} = \frac{1}{2\mu_0}\left(\frac{\vec{E}^2}{c^2} - \vec{B}^2\right) \qquad \mathcal{G} = \frac{1}{\mu_0}\frac{\vec{E}}{c}\cdot\vec{B}\ .$$

$$\frac{\nabla}{\mu_0} \times \left(\frac{\partial \mathcal{L}}{\partial \mathcal{F}}\vec{B} - \frac{1}{c}\frac{\partial \mathcal{L}}{\partial \mathcal{G}}\vec{E}\right) = \vec{j} + \frac{\epsilon_0}{\partial t}\left(\frac{\partial \mathcal{L}}{\partial \mathcal{F}}\vec{E} + c\frac{\partial \mathcal{L}}{\partial \mathcal{G}}\vec{B}\right)\ . \tag{18}$$

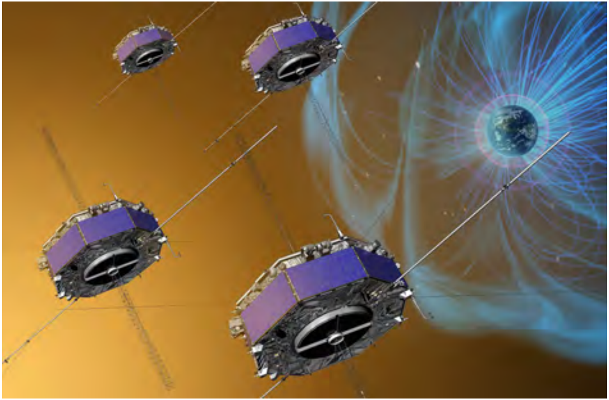
Equations (16,17,18) can be cast as

$$\vec{j}_B = \vec{j}_P + \underbrace{\vec{j}_E}_{negligible} + \vec{j}_{nM}\ , \qquad \text{DIFFERENCE!} \tag{19}$$

where $\vec{j}_B = \nabla \times \vec{B}/\mu_0$, $\vec{j}_P = \vec{j}$, $\vec{j}_E = \epsilon_0(\partial\vec{E}/\partial t)$, and $\vec{j}_{nM}$ is the non-Maxwellian term.

MMS

We analyse the Ampère-Maxwell law, through the NASA Magnetospheric Multiscale Mission (MMS), as it has been done for the ESA Cluster satellites. MMS was launched on 13 March 2015, and it is composed of four identical satellites flying in tetrahedral formation, passing through different zones of the Earth neighbourhood. The instruments on board include particle detectors and magnetometers.

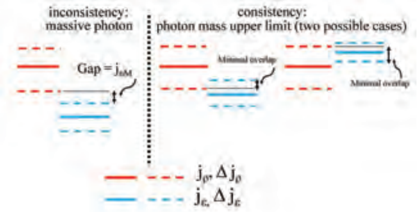


Comparison of currents

We compared, at each second, $\vec{j}_B$ with $\vec{j}_P$. "Inconsistency" (gap) if the two currents including the error bands do not overlap; "Consistency" otherwise

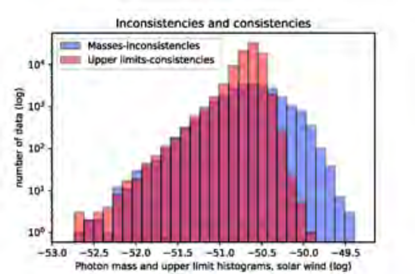
$$|\vec{j}_\rho| - \Delta|\vec{j}_\rho| - \left(|\vec{j}_\epsilon| + \Delta|\vec{j}_\epsilon|\right) = \overset{gap}{\underset{overlap}{\gtrless}} 0 \ , \tag{20}$$

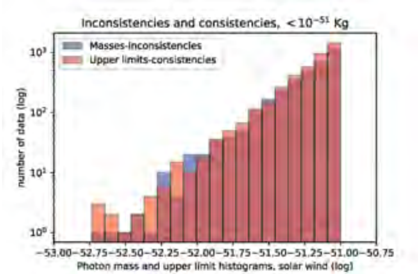
where $\rho, \epsilon = B, P$ depending on whether $|\vec{j}_P| - \Delta|\vec{j}_P|$ is larger or smaller than $|\vec{j}_B| - \Delta|\vec{j}_B|$.



The red and blue lines represent the currents, and, if dotted, the error bounds. On the left, the case of inconsistency, where the gap implies $\vec{j}_{nM} \neq 0$. On the right, the case of consistency, for which moving upward or downward one of the two bands, we would fall in the inconsistency case, finding just an upper limit for $\vec{j}_{nM}$. This computation has been carried out for the modulus and for each component.

Is Ampère-Maxwell law verified? Not in the Solar Wind?





MMS is not a dedicated mission to fundamental physics. Most measurements are performed in noy suitable zones. But the Solar Wind zone is more suitable. The AM is not verified in 29.7% of the cases (45.2% for feeble currents). Likely mismatches between currents even after instrument calibration and analysis of systematic effects on MMS are still present.

Particle Data Group

Citation: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

γ (photon) $I(J^{PC}) = 0,1(1^{--})$

γ MASS

Results prior to 2008 are critiqued in GOLDHABER 10. All experimental results published prior to 2005 are summarized in detail by TU 05.

The following conversions are useful: $1\ \text{eV} = 1.783 \times 10^{-33}\ \text{g} = 1.957 \times 10^{-6}\ m_e$; $\bar{\lambda}_C = (1.973 \times 10^{-7}\ \text{m}) \times (1\ \text{eV}/m_\gamma)$.

VALUE (eV)	CL%	DOCUMENT ID		COMMENT
$<1 \times 10^{-18}$		[1] RYUTOV	07	MHD of solar wind
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.2 \times 10^{-14}$		[2] BONETTI	17	Fast Radio Bursts, FRB 121102
$<1.8 \times 10^{-14}$		[3] BONETTI	16	Fast Radio Bursts, FRB 150418
$<1.9 \times 10^{-15}$		[4] RETINO	16	Ampere's Law in solar wind
$<2.3 \times 10^{-9}$	95	[5] EGOROV	14	Lensed quasar position
		[6] ACCIOLY	10	Anomalous magn. mom.
$<1 \times 10^{-26}$		[7] ADELBERGER	07A	Proca galactic field
no limit feasible		[7] ADELBERGER	07A	γ as Higgs particle
$<1 \times 10^{-19}$		[8] TU	06	Torque on rotating magnetized toroid
$<1.4 \times 10^{-7}$		ACCIOLY	04	Dispersion of GHz radio waves by sun
$<2 \times 10^{-16}$		[9] FULLEKRUG	04	Speed of 5-50 Hz radiation in atmosphere
$<7 \times 10^{-19}$		[10] LUO	03	Torque on rotating magnetized toroid
$<1 \times 10^{-17}$		[11] LAKES	98	Torque on toroid balance
$<6 \times 10^{-17}$		[12] RYUTOV	97	MHD of solar wind
$<8 \times 10^{-16}$	90	[13] FISCHBACH	94	Earth magnetic field
$<5 \times 10^{-13}$		[14] CHERNIKOV	92	Ampere's Law null test
$<1.5 \times 10^{-9}$	90	[15] RYAN	85	Coulomb's Law null test
$<3 \times 10^{-27}$		[16] CHIBISOV	76	Galactic magnetic field
$<6 \times 10^{-16}$	99.7	[17] DAVIS	75	Jupiter's magnetic field
$<7.3 \times 10^{-16}$		HOLLWEG	74	Alfven waves
$<6 \times 10^{-17}$		[18] FRANKEN	71	Low freq. res. circuit
$<2.4 \times 10^{-13}$		[19] KROLL	71A	Dispersion in atmosphere
$<1 \times 10^{-14}$		[20] WILLIAMS	71	Tests Coulomb's Law
$<2.3 \times 10^{-15}$		GOLDHABER	68	Satellite data

Lagrangian
$\longrightarrow$ Field equation
$\longrightarrow$ Field = background + photon
$\longrightarrow$ Photon energy-momentum tensor density

A photon crosses an EM or LSV background. We split the EM field F and the 4-potential A in the background B (capital letters) and photon (small letters)

$$A^\beta = A^\beta_{\rm B} + a^\beta\ , \qquad F^{\alpha\beta} = F^{\alpha\beta}_{\rm B} + f^{\alpha\beta}\ , \qquad G^{\alpha\beta} = G^{\alpha\beta}_{\rm B} + g^{\alpha\beta}\ . \tag{21}$$

The scalar fields $\mathcal{F}$ and its dual $\mathcal{G}$ are

$$\mathcal{F} = -\frac{1}{4\mu_0}F^2 = -\frac{1}{4\mu_0}F_{\sigma\tau}F^{\sigma\tau} = \frac{1}{2\mu_0}\left(\frac{\vec{E}^2}{c^2} - \vec{B}^2\right)\ , \tag{22}$$

$$\mathcal{G} = -\frac{1}{4\mu_0}FG = -\frac{1}{4\mu_0}F_{\sigma\tau}G^{\sigma\tau} = \frac{1}{\mu_0}\frac{\vec{E}}{c}\cdot\vec{B}\ , \tag{23}$$

where $F_{\sigma\tau}$ is the electromagnetic field tensor and $G^{\sigma\tau} = \frac{1}{2}\epsilon^{\sigma\tau\alpha\beta}F_{\alpha\beta}$ is its dual; $\mu_0 = 4\pi\times 10^{-7} \approx 1.256$ H m^{-1} or V s A^{-1} m^{-1} is the vacuum permeability.

Frequency shift: what does it imply

SI units, photon energy-momentum tensor density [Jm^{-3}].
${\theta^0}_0$ = energy density,
${\theta^0}_k$ = energy flux divided by c along the k direction,
${\theta^k}_0$ = momentum density through the orthogonal surface to k, multiplied by c.
The derivative of the energy-momentum density tensor [Jm^{-4}].

$$\partial_\alpha {\theta^\alpha}_\tau \neq 0 \longrightarrow \Delta\nu \tag{24}$$

The photon exchanges energy with the background.

Wave-Particle correspondence $\longrightarrow$ red or blue shift.

Superposing the shifts. z_C is due to expansion; z_S static due to ETEM.

- $z = \Delta\nu/\nu_o$ where $\Delta\nu = \nu_\mathrm{e} - \nu_o$ is the difference between the observed ν_o and emitted ν_e frequencies, or else $z = \Delta\lambda/\lambda_\mathrm{e}$ for the wavelengths.
- Expansion causes λ_e to stretch to λ_c that is $\lambda_\mathrm{c} = (1 + z_\mathrm{C})\lambda_\mathrm{e}$. The wavelength λ_C could be further stretched or shrunk for the ETE shift to $\lambda_\mathrm{o} = (1 + z_\mathrm{S})\lambda_\mathrm{c} = (1 + z_\mathrm{S})(1 + z_\mathrm{C})\lambda_\mathrm{e}$. But since $\lambda_\mathrm{o} = (1 + z)\lambda_\mathrm{e}$, we have $1 + z = (1 + z_\mathrm{C})(1 + z_\mathrm{S})$.

The second order is not negligible for larger z_C.

$$z = z_\mathrm{C} + z_\mathrm{S} + z_\mathrm{C} z_\mathrm{S} \ . \tag{25}$$

Frequency shifts

$$\partial_\alpha \theta^\alpha{}_\tau|_{\rm dBP} = \underbrace{j^\alpha f_{\alpha\tau} - \frac{1}{\mu_0}(\partial_\alpha F^{\alpha\beta})f_{\beta\tau}}_{\text{Maxwellian terms}} + \underbrace{\frac{1}{\mu_0}\mathcal{M}^2(\partial_\tau A^\beta)a_\beta}_{\text{de Broglie-Proca term}} \ . \tag{26}$$

$$\partial_\alpha \theta^\alpha{}_\tau|_{\rm LSV} = {\rm MT} - \frac{1}{\mu_0}\left[\underbrace{\frac{1}{2}\left(\partial_\alpha k_\tau^{\rm AF}\right) g^{\alpha\nu} a_\nu - \frac{1}{4}\left(\partial_\tau k_{\rm F}^{\alpha\nu\kappa\lambda}\right) f_{\alpha\nu} f_{\kappa\lambda}}_{\text{EM background independent terms}} + \underbrace{\partial_\alpha\left(k_{\rm F}^{\alpha\nu\kappa\lambda} F_{\kappa\lambda}\right) f_{\nu\tau}}_{\text{non-constant term}} + \underbrace{k_\alpha^{\rm AF} G^{\alpha\nu} f_{\nu\tau}}_{\text{constant term}}\right] . \tag{27}$$

$$\partial_\alpha \theta^\alpha{}_\tau|_{\rm NLEM} = {\rm MT} \underbrace{- \frac{1}{\mu_0}\partial_\alpha C_2 \tilde{F}^{\alpha\nu} f_{\nu\tau}}_{\text{non-Maxwellian linear term}} \underbrace{+ \frac{1}{4\mu_0}\left(\partial_\tau C_1\right) f^{\alpha\nu} f_{\alpha\nu} + \frac{1}{4\mu_0}\left(\partial_\tau C_2\right) \tilde{f}^{\alpha\nu} f_{\alpha\nu} - \frac{1}{8\mu_0^2}\left(\partial_\tau \hat{Q}^{\alpha\nu\kappa\lambda}\right) f_{\alpha\nu} f_{\kappa\lambda}}_{\text{second order non-linear terms}}$$

$$\underbrace{- \frac{1}{8\mu_0^3}\left(\partial_\tau R^{\alpha\nu\kappa\lambda\rho\sigma}\right) f_{\alpha\nu} f_{\kappa\lambda} f_{\rho\sigma} - \frac{1}{16\mu_0^4}\left(\partial_\tau S^{\alpha\nu\kappa\lambda\rho\sigma\omega\xi}\right) f_{\alpha\nu} f_{\kappa\lambda} f_{\rho\sigma} f_{\omega\xi}}_{\text{third and fourth non-linear terms}} \ . \tag{28}$$

$$\left.\frac{\partial \mathcal{L}}{\partial \mathcal{F}}\right|_{\rm B} = C_1 \quad \left.\frac{\partial \mathcal{L}}{\partial \mathcal{G}}\right|_{\rm B} = C_2 \quad \left.\frac{\partial^2 \mathcal{L}}{\partial \mathcal{F}^2}\right|_{\rm B} = D_1 \quad \left.\frac{\partial^2 \mathcal{L}}{\partial \mathcal{G}^2}\right|_{\rm B} = D_2 \quad \left.\frac{\partial^2 \mathcal{L}}{\partial \mathcal{F}\partial \mathcal{G}}\right|_{\rm B} = D_3 \ , \tag{29}$$

Sizing the effect from physics

The size determines whether the interest is for cosmology or ONLY for physics. How to compute it?

- Magnitude and direction of B (LSV) in the source galaxy where photons are emitted.
- Magnitude and direction of B (LSV) in the intergalactic space.
- The alignment of these fields.
- Definition and values of electric and magnetic fields for a photon.
- There are up to 24 orders of magnitude between experimental LSV coefficients and astrophysical observations/models.

We can get values of the static shift ranging from 0.01% to 10% of the expansion shift.

Sizing the effect from cosmology: dark energy

What is the static frequency shift that I need to get rid of dark energy?

1. The *single* $z_{\rm S}$ shift from a **single** SNIa may be small or large, red or blue, depending on the orientations of the LSV (vector or tensor) and of the EM fields, as well as the distance of the source. Anyway, the colour of $z_{\rm S}$ is the final output of a series of shifts, both red and blue, encountered along the path.
2. If the $z_{\rm S}$ shift is blue, the photon gains energy; it implies that the real z, traditionally the red-shift, is larger than the measured z, as $z_{\rm S}$ is subtracted from $z_{\rm C}$, the expansion red-shift. If red, $z_{\rm S}$ corresponds to dissipation along the photon path; it implies that the real z is smaller than the measured z, as $z_{\rm S}$ is added to $z_{\rm C}$.

Sizing the effect from cosmology: no dark energy $\Omega_\lambda = 0$ an extreme case

- We have tested our prediction considering the Pantheon and Pantheon + Catalogues. The frequency shift z_S may support an alternative to accelerated expansion, naturally accommodating each SN Ia position in the distance modulus versus red shift diagram, due to the light-path dependency of z_S.
- Cosmology model A: we set $\Omega_M = 0.3$ and consider $\Omega_K = 0$, implying a flat universe where the "cosmic triangle" relation $\Omega_M + \Omega_K + \Omega_\Lambda = 1$, is not satisfied *ab initio*. Nevertheless, the dark energy effect could be replaced *a posteriori* by the effect of z_{S}. This approach supposes that z_{S} is a manifestation of the LSV vacuum energy in string models, in case of the SME.
- Cosmology model B: we take into account an open universe model, where $\Omega_M = 0.3$ and $\Omega_K = 0.7$, so that $\Omega_K + \Omega_M = 1$.
- Cosmology model C: we return to the Einstein-de Sitter conception, that is a flat, matter dominated universe with $\Omega_M = 1$. This was one of the most popular cosmological model before the advent of the Dark Energy hypothesis.

Sizing the effect from cosmology: dark energy

EPJ+.jpg

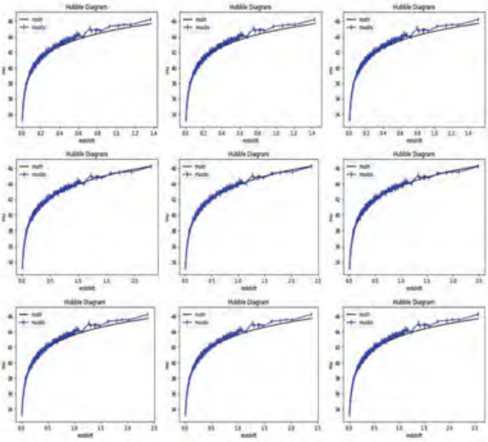


Figure: Through the Hubble diagrams, we compare the three cosmological models A, B, C, each for row, based upon the best fit values of k_1 with data from the Pantheon Sample (1084 SNe Ia), with three values of H_0 (67, 70, 74 km s^{-1} per Mpc), each for column. The black lines represent the models, while the blue marks trace the SNe Ia data with their errors.

Frequency shift: tests

We can set, though, an upper limit by absurd: supposing expansions does not occur and the red shift comes only from an ETEM static effect.
The Hubble-Lemaître constant is around 70 km s^{-1} per Mpc, which in a laboratory setting is 2.3×10^{-18} m s^{-1} per m. Dividing by c, we obtain $7.7 \times 10^{-27} \Delta\nu/\nu$ per m.

Digression on expansion

Cosmology states that the expansion starts at extra-galactic scale (not below). Therefore, this experiment would verify the absence of expansion at small scale.

Is expansion falsifiable in a lab? Conceptually is impossible, technically is hard (no expansion above 1% of H_0)

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Frequency shift: tests of upper limits

- Table 1 shows for four different configuration, the relative and absolute frequency shift for an optical frequency of 600 THz.
- Feasibility of cavity and delay lines for the extra optical path (Earth-Moon distance mimicked).
- A possible design would consist of an interferometer with arms of different lengths with a spectrometer at the end. The transition lines would be activated or not depending on the impinging frequency.
- Three considerations for or against the measurement. 1 - - cavity length changes disturb the measurements. 2 ++ Only relative, not absolute, frequency stability is required between the two arms. 3 Magnetic field modulation is likely beneficial.

Method	$\Delta\nu/\nu$	$\Delta\nu$ for $\nu = 6 \times 10^{14}$ Hz
1 km (LIGO-Virgo like)	7.7×10^{-24}	4.6 nHz
10 km (Einstein Telescope)	7.7×10^{-23}	46 nHz
380.000 km (Moon)	3×10^{-18}	1.8 mHz
2.5 million km (LISA)	2×10^{-17}	12 mHz

Table: Upper limits frequency shifts for interferometry of different length. The displayed values in the Table refer to a single one-way shift. The shifts may accumulate at each transmission from one mirror to the other. Cavities and delay lines may enhance the optical length.

Conclusions and perspectives, what next

- Casting doubts on Maxwellian EM may change the vision of the universe. But even the effects would be too small for cosmology, their successful testing would be of importance for fundamental physics. Further, mixed scenarii are possible: dark + ETEM together (a less dark universe)
- There are running experiments (Toulouse, Paris, Padova, CERN) for ETEM testing. They aim to measure birefrigence, second order QED, through different means including strong magnetic fields.
- We are tackling rotation curves. Without recurring to dark matter or other theoris of gravity, we are attempting to explain rotation curves by considering the interactions of the photons with the rotating galactic magnetic fields.
- The mechanisms (de Broglie-Proca, Born-Infeld and Heisenberg-Euler, Standard-Model Extension) we have found so far produce a shift toward the red or the blue. We are now attempting to study a mechanism that would produce only a red-tired shift to be added to the expansion shift and thereby comply with some interpretations of JWST data.

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